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NAVAL POSTGRADUATE SCHOOL

Monterey, California

DETERMINING OPTIMAL INSTRUCTOR LEVELS AT THE DEFENSE LANGUAGE INSTITUTE

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December 1993

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Determining Optimal Instructor Levels at the Defense Language Institute

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Abstract

The Defense Language Institute (DLI) teaches various levels of foreign language competency to Department of Defense personnel. It currently offers instruction in 23 languages using 104 courses that range in length from 2 to 63 weeks. Student input and a mandated instructor-to-student ratio determine the number of sections of each course that must be taught each year. This paper develops integer linear programs to decide when to start each section of each course. The primary objective is to minimize the number of full-time instructors required to meet the next three years' student input. Secondary objectives are used to improve the face validity of the models' recommendations. When compared with current manual methods, decisions developed using the models are superior for all measures of effectiveness considered, and they provide DLI with a savings opportunity in excess of $7 million over the next three years.

The Defense Language Institute (DLI), located in Monterey, CA, teaches 10% of all United States post-secondary foreign language instruction. It currently offers 23 languages using 104 courses that range in length from 2 to 63 weeks. The United States Armed Forces and several federal agencies are awarded yearly quotas' for each of these courses, based on their projected requirements. The Department of Defense (DoD) mandates each section of a course contain no more than ten students and have exactly two instructors. (DoD allows sections of 5 students or less with only one instructor, but DLI prefers sections of ten students.) This mandated instructor-to-student ratio and preference defines the exact number of sections of each course that must be taught each year. The DLI scheduler decides which week of the year to start each section of all courses. (The course does not have to be completed in the year it starts.) The overall objective guiding this decision making process is to minimize the full-time staff of instructors required to meet the yearly student input. This paper derives and solves integer programming models to assist the scheduler.

Prior to the development of these models, the DLI scheduler took approximately six weeks to create a *master schedule* (a list with one year's weekly section start dates for each language). The master schedule often had significant periods with under-utilized instructors and planned for only one year's student input. Time limited the scheduler from fully utilizing the yearly projections available for the next three years. Presure on DLI to operate cost effectively and accommodate changes in year to year course demands motivated them to find a better way to use their instructor resources.

The DLI scheduler and program analyst assisted us with all relevant information as our research progressed (*e.g.*, Kunzman 1993). DLI and the Naval Postgraduate School (NPS) are within five miles of each other which not only helped during our modeling phase but figured in the choice of both software and platform. We formulate and solve all models using GAMS (Brooke, Kendrick, and Meeraus 1992) and XA (Sunset Software, 1987) on the NPS AMDAHL 5990-700A mainframe under the VM operating system. DLI has access to the NPS mainframe and available software, allowing them to implement the model at no cost.

The problem of creating the DLI master schedule is a unique scheduling/timetabling problem. It is most similar in structure to a bin packing problem (see Garey and Johnson 1979) and in topic to course and examination timetabling problems (see Carter 1986). These timetabling problems are both concerned with a fixed work force, in contrast to the DLI problem which seeks the appropriate size for the work force (much like a bin packing problem seeks the minimum number of bins). The differences between a bin packing problem and the problem of creating the DLI master schedule becomes apparent in the next section.

Section 1) outlines policies for creation of the DLI master schedule; 2) presents the integer programs developed to assist the scheduler; 3) provides computational experience including detailed comparisons with manual solutions; 4) summarizes conclusions; the appendix gives a proof that the simplest version of the problem is NP-complete.

1 The DLI Master Schedule

The overall problem of creating the master schedule is separable by language since instructors teach only one language and classroom space and living quarters are ample for any implementable schedule. For each language, the DLI scheduler's input is the number of sections of each course that must be taught each year and the number of ongoing sections extending into the year under consideration. The scheduler must start each required section during the appropriate year but the course may finish in a later year.

Restrictions on instructor use apply to all languages taught at DLI and include:

- The use of full-time instructors only,
- Instructors are employed on a yearly basis,
- Instructors can teach only one section at a time.

The restrictions on section starts include:

- DLI observes a yearly holiday period the last two weeks of December (for modeling purposes, this mandatory break allows the use of a 50-week year).
- DLI restricts any courses from beginning one month before the two-week holiday. Courses may be scheduled to end during this period.

- Preparation required for graduation (*e.g.*, final proficiency exams) imposes a restriction on courses ending earlier than the third week after the two-week holiday.
- DLI prefers to start three (but no more than three) sections of a course in one week.

Subject to these restrictions, the scheduler attempts to produce a master schedule with the minimum number of instructor years. (The Appendix shows this problem for only one language and year to be NP-complete in the strong sense.) The scheduler also attempts, as long as it does not increase instructor years, to start three sections of one course together.

2 OSI for DLI

DLI desires the master schedule to have several characteristics. Foremost is cost minimization which directly translates into the first objective:

1. Minimize the number of instructor years.

A model with only this objective produces face-valid results. The following secondary objectives capture other desired features:

2. Minimize fluctuation in year-to-year instructor totals.
3. Maximize the number of three section starts.
4. Minimize instructor downtime.

We implement each objective in a separate model where the limited results of previous models (or trial values supplied by the scheduler) are sequentially carried forward as data for the next model. (*i.e.*, First minimize the number of instructor years. Then for all schedules with the minimum number of instructor years, choose the one with the most consistent yearly instructor requirement.) The separate models are computationally easier to solve and allow the scheduler the requested flexibility to investigate the effects of varying key parameters.

The resulting models are called OSI (Optimally Scheduling Instructors) for DLI. For clarity, OSI_k refers to the OSI model using only objective k (*i.e.*, OSI_1 is the model with objective one only). OSI_1's formulation directly follows the introduction of notation. Models using other objective functions follow any new or changed notation.

2.1 OSI_1

- Indices:

i	course,
t, t'	weeks DLI is in session (1-150),
y	schedule year (1-3).

- Data:

$start_{it}$	1 if course i can begin in week t and 0 otherwise (this parameter enforces scheduling restrictions related to the two-week holiday),
$pcdur_t$	number of sections in session during week t due to past scheduling decisions,
$section_{iy}$	number of sections of course i that require scheduling in year y,
$length_i$	length of course i (in weeks),

- Decision Variables:

x_{it}	number of sections of course i to start in week t (positive integer),
$tmax_y$	maximum number of simultaneous sections meeting in year y (with x_{it} restricted to be a positive integer this variable is implicitly a positive integer).

- OSI_1:

$$\text{minimize } \sum_y 2\, tmax_y$$

subject to constraints :

$$\sum_{t=(1+50(y-1))}^{50y} start_{it} x_{it} = section_{iy} \quad \forall i, y \tag{1}$$

$$\sum_i \sum_{t'=t-length_i}^{t} start_{it'} x_{it'} + pcdur_t \le tmax_{\lfloor (t-1)/50 \rfloor + 1} \quad \forall t \tag{2}$$

(1) Yearly section requirements for course i must be scheduled.

(2) Defines maximum number of simultaneous sections meeting in any week t for each year y.

An upper bound of three is imposed on x_{it} in OSI_1 and OSI_2. (It is subsequently relaxed in OSI_3 and OSI_4.)

2.2 OSI_2

OSI_2 minimizes changes in the number of instructors from year-to-year while ensuring that no more than $totinst$ (the objective function value of OSI_1) are used.

- Data:

$totinst$	Maximum number of instructor years.
$tmax_0$	Half of the number of instructors employed for the year prior to the models planning horizon.
$smooth_y$	Penalty for changing instructor levels in year y.

- Decision Variables:

$more_y$ Additional instructors needed at the beginning of year y (positive integer),

$less_y$ Possible instructor reduction at the beginning of year y (positive integer).

- OSI_2:

$$\text{minimize } \sum_y smooth_y(more_y + less_y)$$

subject to constraints : (1), (2), and

$$2(tmax_y - tmax_{y-1}) \leq more_y \ \ \forall y \tag{3}$$

$$2(tmax_{y-1} - tmax_y) \leq less_y \ \ \forall y \tag{4}$$

$$\sum_y 2\ tmax_y \leq totinst \tag{5}$$

(3) Defines additional instructors needed for year y.

(4) Defines possible instructor elimination for year y.

(5) Instructor year total cannot exceed a maximum.

Giving the first year (the year with the most accurate data) a higher value of $smooth_y$ empirically provides a smooth transition from previous instructor year totals into the models implementable instructor year totals. (OSI_2 uses $smooth_1 = 100$, $smooth_2 = 10$, and $smooth_3 = 1$ for the results reported in section 3.)

2.3 OSI_3

OSI_3 maximizes the number of three section starts while restricting the number of instructors in each year to the value determined by OSI_2. OSI_3 uses different notation from OSI_1 and OSI_2. It has a third index on the decision variable which counts the number of simultaneous section starts.

- Indices:

s number of sections to simultaneously start (1-3).

- Data:

$stackit_{sit}$ value of starting s section(s) of course i in week t,

$tmax_y$ one half of the instructor year total for year y (output from OSI_2),

$sec3max_{iy}$ maximum number of three section starts for course i in year y.

- Binary Decision Variables:

x_{sit} 1 if s sections of course i start in week t and 0 otherwise.

- OSI_3:

$$\text{maximize} \sum_s \sum_i \sum_t stackit_{sit} x_{sit}$$

subject to the constraints :

$$\sum_s \sum_{t=(1+50(y-1))}^{50y} s \times start_{it} \times x_{sit} = section_{iy} \;\; \forall i, y \tag{6}$$

$$\sum_s \sum_i \sum_{t'=t-length_i}^{t} s \times start_{it'} \times x_{sit'} + pcdur_t \leq tmax_{\lfloor (t-1)/50 \rfloor + 1} \;\; \forall t \tag{7}$$

$$\sum_{t=(1+50(y-1))}^{50y} x_{3it} \leq sec3max_{iy} \;\; \forall i, y \tag{8}$$

(6) Equivalent to constraint (1) reformulated for the redefined decision variable.

(7) Equivalent to constraint (2) reformulated for the redefined decision variable.

(8) Sets upper bound on the yearly number of three section starts for each course.

Constraint (8) provides valid inequalities that reduce possible fractional variables in the linear programming relaxation. For example, if 11 sections require scheduling, then there are at most 3 three-section starts possible. Without constraint (8), the remaining two sections would be encouraged to have some $x_{3it} = 2/3$ in the linear programming relaxation.

Objective function coefficients, like those in OSI_2, which emphasize year one's three section starts (the year with the most accurate data) empirically produced desirable results. (OSI_3 uses $stackit_{3i1} = 100$, $stackit_{3i2} = 10$, and $stackit_{3i3} = 1$ for results reported in section 3.)

OSI_3 limits the number of simultaneous section starts per course per week to six (*i.e.*, for a specific course, i, and week, t, x_{3it}, x_{2it}, and x_{1it} can all equal one resulting in six section starts). Explicit constraints could be added to limit the total to the DLI preference, three, but were not needed in practice.

2.4 OSI_4

OSI_4 maximizes the amount of each section completed in the year it starts while maintaining values obtained by the previous models.

- Data:

$num3sect_{iy}$	number of three section starts (output from OSI_3),
$pushback_{sit}$	value of starting s section(s) of course i in week t.

- OSL_4:

$$\text{maximize } \sum_s \sum_i \sum_t pushback_{sit} x_{sit}$$

subject to constraints : (6), (7), and

$$\sum_{t=(1+50(y-1))}^{50y} x_{3it} \geq num3sect_{iy} \quad \forall i, y \tag{9}$$

(9) Sets the lower bound on the number of yearly three section starts for each course.

The objective function coefficient, $pushback_{sit}$, is based on the minimum of 1 and $(50y - t)/length_i$ (the percent of each course completed during the year it started). As an example, a 20-week course starting in week 132 of a 150-week schedule would receive a fractional value of 18/20. This provides an incentive to complete as much of a course as possible during the year in which it starts. Included in $pushback_{sit}$ is a multiplicative constant to account for the year and number of simultaneous section starts. The weighted values for 3, 2 and 1 section starts are; 300, 200, 100 (Year 1); 30, 20, 10 (Year 2) and 3, 2, 1 (Year 3).

An alternate objective of maximizing the completion of as many courses as possible before the end of the fiscal year was considered for OSL_4. Unfortunately, overlap is inevitable for most schedule years and the explicit maximization of the number of completed courses during the fiscal year empirically produces a non-implementable schedule. The reason for this can be explained with a simple example. Consider a 50-week schedule in which two 15-week courses and two 36-week courses must be scheduled. Figure I shows optimal solutions for both OSL_4 and maximizing the number of course completions. Maximizing the number of course completions produces significantly more overlap and idle time.

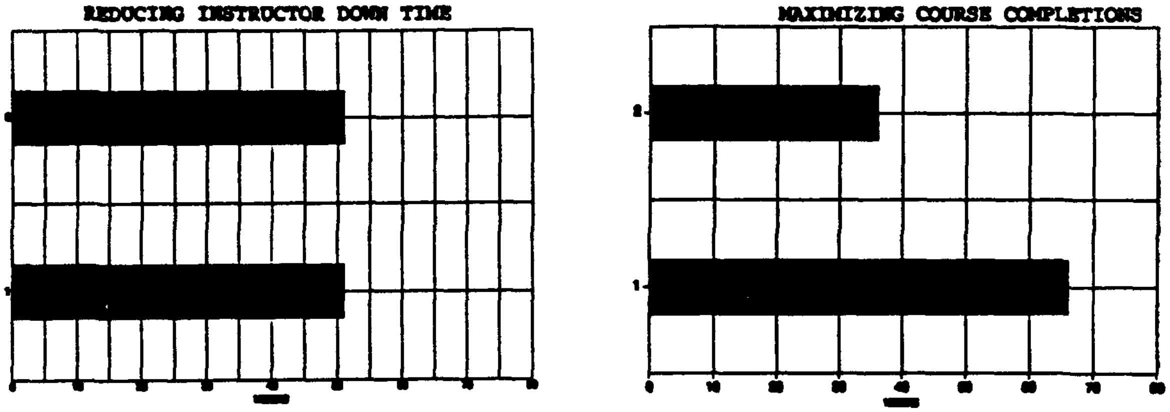

Figure I: *Maximizing the number of course completion produces significantly more overlap and idle time. An optimal solution for OSI, shown on the left, has no instructor idle time for the 2 instructors and only 2 of the 102 instruction weeks not completed within the 50 week year. This compares to the alternate objective with 14 idle weeks and 16 instruction weeks not completed within the year.*

3 Computational Experience

DLI offers instruction in 23 languages shown in Table I ordered by 1994 section totals. Of these languages, we solve 19 using OSI since the other four require few instructors and are easily scheduled manually. Three languages (Arabic, Spanish, and German) are chosen for extensive OSI testing based on their variation in course lengths, the number of sections requiring scheduling, the number of courses offered, and conversations with the DLI scheduler and program analyst. The integer linear program size of each representative data set varies with the version of OSI as summarized in Table II. All tests of OSI are done using DLI data for fiscal years 1994, 1995 and 1996, shown in Table III.

Due to various course lengths, some sections of courses are in session dur-

Language	FY 94		Course Lengths	
	Courses	Sections	Minimum	Maximum
Russian	8	63	2	47
Arabic	8	60	2	63
Spanish	6	60	2	25
Korean	6	35	2	63
Chinese	3	17	47	63
German	7	13	2	34
French	4	10	2	25
Czechoslovakian	6	9	2	47
Vietnamese	5	8	2	47
Persian	5	8	2	47
Polish	5	8	2	47
Japanese	6	6	2	63
Turkish	6	5	2	47
Thai	4	5	16	47
Italian	5	4	2	25
Hebrew	4	4	2	47
Ukrainian	2	3	2	47
Tagalog	5	3	2	47
Portuguese	4	3	8	25
Dutch	3	2	18	25
Greek	4	1	16	47
Belorussian	1	1	47	47
Serbo-Croatian	0	0	12	12

Table I: ***FY 94 LANGUAGE CHARACTERISTICS. This table shows the relative size and diversity of the languages taught at DLI for fiscal year 1994.***

Language	OSI_k	Variables	Constraints	Non-zeros
German	1	438 (Integer)	172	21,060
	2	438 (Integer)	179	21,084
	3	700 (Binary)	175	63,919
	4	700 (Binary)	175	65,956
Spanish	1	620 (Integer)	172	18,949
	2	620 (Integer)	179	18,973
	3	1,070 (Binary)	180	57,836
	4	1,070 (Binary)	180	59,873
Arabic	1	645 (Integer)	175	44,861
	2	645 (Integer)	182	44,885
	3	1,419 (Binary)	186	135,872
	4	1,419 (Binary)	186	138,200

Table II: *OSI MODELS SIZE. German, Spanish and Arabic for fiscal years 1994, 1995 and 1996 are used for extensive OSI testing.*

ing more than one fiscal year. The parameter $pcdur_t$, found in constraints (2) and (7) account for any previously scheduled sections requiring consideration in OSI. This parameter is easily formed from the number of sections and weeks they extend into fiscal year 1994, contained in Table IV.

Data from the German language is representative of small data sets. There are, on average, 13 sections to schedule for each fiscal year, as shown in Table III. Course lengths do not exceed 34 weeks allowing substantial scheduling flexibility. There are several courses overlapping into the new fiscal year schedule, as shown in Table IV. A unique case in the overlap is the existence of half a section (five students or less requiring only one instructor) being scheduled into the new fiscal year schedule.

Data from the Spanish language represents an intermediate data set requiring the scheduling of four times as many sections as the German language.

Language	Course Length	Number of Sections		
		1994	1995	1996
German	34	10	8	9
	26	1	2	2
	24	1	0	2
	2	1	1	2
Spanish	25	51	51	53
	18	8	6	6
	10	0	1	1
	2	1	3	3
Arabic	47	3	4	4
	2	1	1	1
	63	56	57	55

Table III: *SUMMARIZED LANGUAGE REQUIREMENTS IN TEST DATA. Fiscal years 1994, 1995 and 1996 course sections needing scheduling based on projected student input.*

It contains a 25-week course that the scheduler deals with in two ways, either as a single 25-week course or the preferred manner, a 50-week course that is counted as two consecutive 25-week courses. There is no standard percentage for determining the 25/50 week mix. Trial and error shows the best mix empirically as nine 25-week courses and 21 50-week courses for fiscal year 1994 and as many 50-week courses as possible for years 2 and 3. Other values empirically result in higher instructor year totals and/or extensive solve times.

Data from the Arabic language represents a large data set. Although the Russian language requires more sections to be scheduled, as shown in Table III, the Arabic language contains a majority of courses 63 weeks in length. This 63-week course provided a substantial challenge for the scheduler and is therefore of great interest as a representative data set.

Table V shows solution times (using the XA default branch and bound scheme) necessary to guarantee an optimal solution and one within 10% of optimal. Table V also reports solution time and quality in parentheses (*i.e.*, (0%) indicates an optimal solution) using a cascading heuristic for OSI_1. The heuristic keeps x_{it} as integer variables in year one, while allowing x_{it} in years two and three to solve as continuous variables. Once solved, $tmax_1$ is fixed to its optimal value and x_{it} in years one and two are constrained to be integer while x_{it} in year three is allowed to be continuous. Upon solving, $tmax_2$ is fixed and the original model is solved.

The program analyst and scheduler verify OSI schedules to be accurate, complete and implementable even when solutions are only guaranteed to be within 10% of optimal. At the 10% level, OSI, including time for data input, produces a three year schedule for one language in less than one hour. It takes the DLI scheduler as much as three days to develop a year's schedule for one language.

OSI instructor year totals over the next three years provide a substantial reduction in projected totals as summarized in Table VI. Further reduction in the OSI totals are possible since the models always assign two instructors to each section (recall sections of five or less students can be scheduled with one instructor but this is not the preferred method). As an example, the models' results for Japanese (36 instructor years) can be reduced to the manually projected total (34 instructor years) since two scheduled sections contain only one student. The average instructor salary with benefits is approximately $64,700 (GS 9, Step 5) (Office Personnel Management, 1992). The results in Table VI show a decrease in instructor year totals over a three year period which equates to potential savings of $7,181,700 over the next three years.

Figure II shows the results of comparing manual versus OSI weekly instructor totals, for each representative data set in fiscal year 1994. As this figure indicates, the OSI schedule produces significantly less fluctuation over

Language	Number of Sections	Length
German	2	3
	2	10
	.5	24
	3	28
Spanish	6	10
	4	16
	9	22
Arabic	5	1
	6	5
	5	10
	5	11
	6	14
	6	18
	6	26
	1	18
	3	33
	6	37
	6	43
	1	46
	6	47
	5	51
	3	56
	3	60

Table IV: ***SUMMARIZED TEST DATA OVERLAP. The number of sections and the length of time they extend into fiscal year 1994. These values are used to form the parameter $pcdur_t$, which indicates the number of instructors committed in each week due to 1993 scheduling decisions.***

Language	OSI_k	10%	0%	cascade
German	1	0.5	**	3.1 (0%)
	2	0.2	**	
	3	1.4	1.4	
	4	20.9	**	
Spanish	1	0.9	0.9	0.6 (0%)
	2	2.7	2.7	
	3	9.9	9.9	
	4	0.5	0.5	
Arabic	1	0.2	0.2	0.5 (0%)
	2	0.1	0.1	
	3	6.5	**	
	4	2.7	**	

Table V: *SOLUTION TIMES. The solution times, in minutes*[1]*, show the ability of OSI to quickly develop schedules that took up to three days to develop manually. Times under the 10% and 0% columns represents the minutes needed to guarantee a solution within the indicated percent of optimal using the XA default branch and bound scheme. The (**) represents a solution time in excess of 30 minutes. Times under the cascade column show the ability of our cascading technique to rapidly obtain solutions verified to be within the percentage of optimal indicated in parentheses.*

[1]Recorded on a 486/33 personal computer running XA version 8. The NPS mainframe has an earlier XA version currently installed. A mainframe upgrade has been purchased.

FY 94, implying less instructor idle time. Manual schedules were not available for fiscal years 1995 and 1996, but as Figure III shows OSI continues to have only minor fluctuations in instructor levels over all weeks.

Figure II indicates OSI provides a larger instructor year total for the Arabic language than manual methods for FY 94 whereas Table VI indicates a three year reduction. The model's FY 94 level of 146 instructors is the same as in FY 93, thus providing no change in instructor levels the first year. It is possible to reduce the FY 94 total from 146 to 144 without increasing the three year total, if reduction is mandated.

Lastly, the ability of OSI to provide a greater number of simultaneous three section starts compared to the manually created total for 1994 is shown in Table VII.

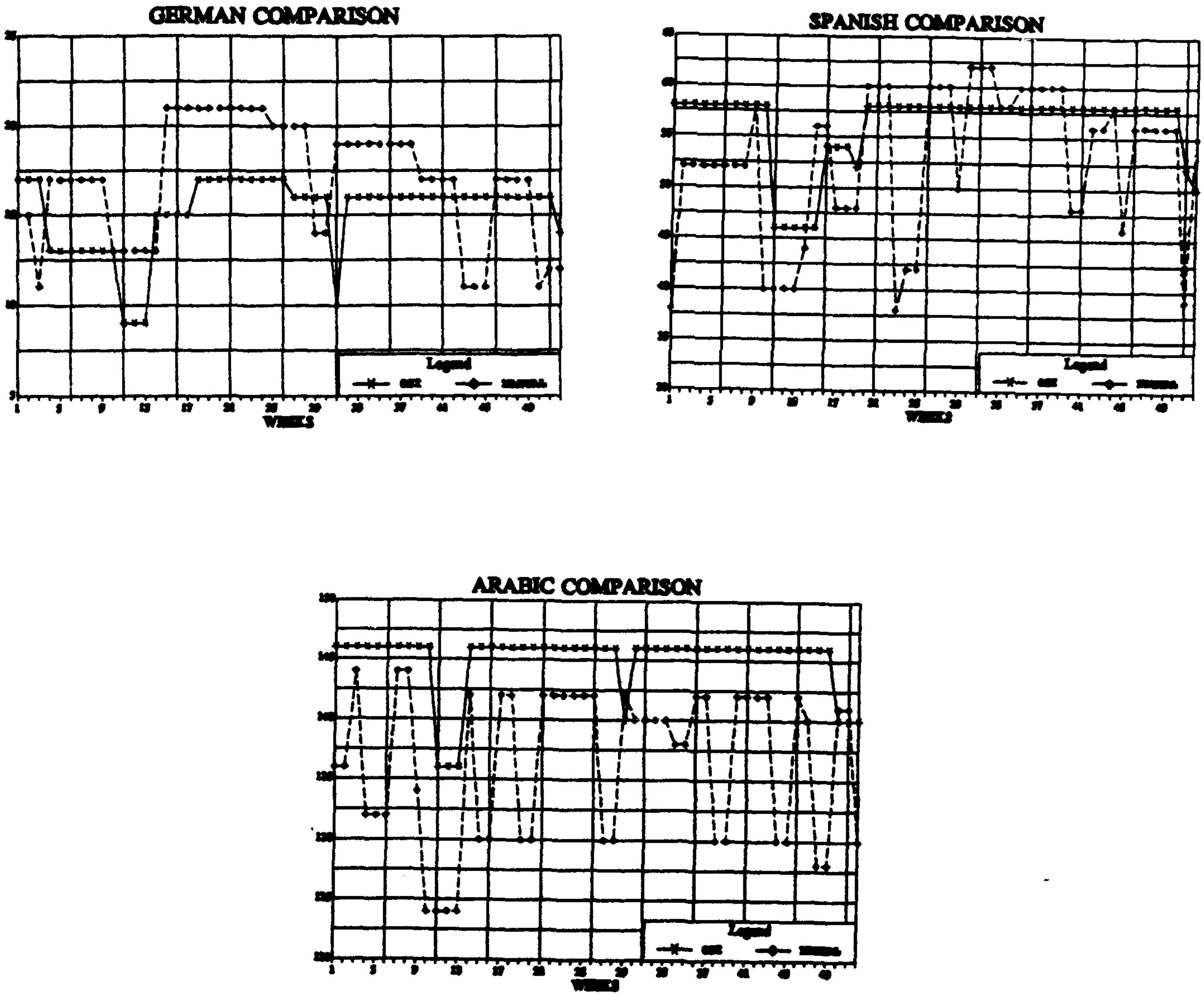

Figure II: *FY94 OSI AND MANUAL SCHEDULES. OSI provides significantly greater instructor utilization.*

Language	Projected Total	OSI Total	Difference	(Cost)/Savings
Russian	377	356	21	$1,358,700
Arabic	438	426	12	$776,400
Spanish	182	164	18	$1,164,600
Korean	226	224	2	$129,400
Chinese	134	128	6	$338,200
German	53	43	10	$647,000
French	35	30	5	$323,500
Czechoslovakian	45	34	9	$582,300
Vietnamese	43	34	9	$582,300
Persian	60	52	8	$517,600
Polish	40	38	2	$129,400
Japanese	34	36	(2)	($129,400)
Turkish	18	14	4	$258,800
Thai	26	26	0	0
Italian	12	12	0	0
Hebrew	28	23	5	$323,500
Ukrainian	18	16	2	$129,400
Tagalog	22	22	0	0
Portuguese	12	12	0	0

Table VI: ***MODEL VERSUS MANUAL COMPARISON. Instructor year totals for fiscal years 94, 95, and 96 using*** **OSI** ***compared to projected manual totals. Cost/Savings is based on salary and benefits of a GS-9 (Step 5).***

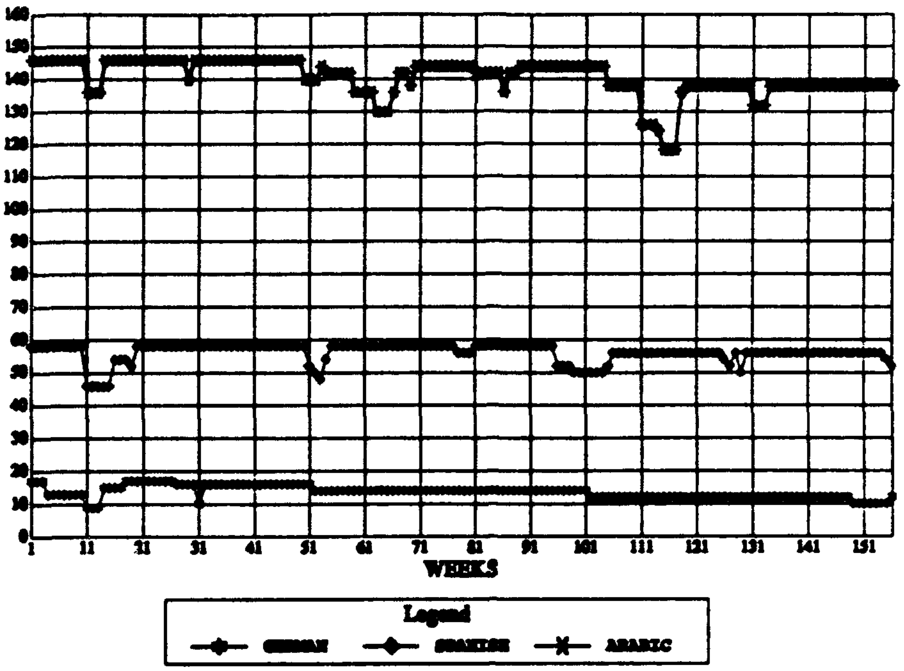

Figure III: *OSI THREE YEAR WEEKLY TOTALS. OSI provides a more constant workforce over the three years.*

Language	Manual	Model
German	3	3
Spanish	15	18
Arabic	9	17

Table VII: *3 SECTION START COMPARISONS. The table shows a comparison of manually scheduled three section starts and the results of* OSI *for FY 94.*

4 Conclusions

OSI produces face-valid schedules in less than one hour for each language which are better than the manually developed schedules in all areas of concern. OSI yields a smaller instructor year total, employs a more constant yearly work-force, and requires significantly less time. The separate objectives provide the scheduler the requested flexibility to review scheduling alternatives quickly and efficiently. OSI develops face-valid results that can be implemented as is; however, its greatest benefit is as an assistant to the DLI scheduler.

The Base Closure and Realignment Commission has forced DLI to investigate alternatives to cut spending. In an attempt to remain open, DLI recently announced the layoff of more than 100 instructors from various languages (The Monterey Herald, July 26, 1993). These layoffs were primarily based on changing language trends. OSI provides DLI the ability to reduce their instructor work-force without sacrificing its mission.

After reviewing OSI results, the program analyst at DLI began steps to permit the implementation of the model. The DLI scheduling office has acquired a NPS mainframe account and updated their hardware to fully implement the model. In August 1994, DLI will plan their 1995 master schedule using OSI.

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Appendix

Consider the problem of determining section start dates for one language during one year (we call this problem the bin overflow problem). An instance of this problem has a finite set of sections S, each section ($s \in S$) lasts a finite number of positive integer weeks $l(s)$, each instructor pair, p, has τ_p positive integer weeks available, and P is the total number of instructor pairs. The bin overflow problem may be stated as the question: is there a partition of S into disjoint sets S_1, S_2, $\cdots$, S_P such that the sum of the length of all but one section, s', in each S_p is strictly less than τ_p for some s' (*i.e.*, $\sum_{s \in S_p \setminus s'} l(s) < \tau_p$ for some $s' \in S_p$). An optimal solution has the minimum number of instructor pairs for which the answer to the question is yes.

Property 1 If an optimal solution to the bin overflow problem exists with P instructor pairs, an optimal solution exists where each instructor pair receives exactly one of the P longest sections.

Assume an optimal solution uses P instructor pairs and violates the property (*i.e.*, some instructor pair(s) do not have any of the P longest sections and therefore some instructor pair(s) have more than one of the P longest sections).

An optimal solution can alway be constructed with Property 1. Take the longest section assigned to an instructor pair without one of the P longest sections and switch it with one of the P longest sections from an instructor pair having more than one. Feasibility continues to exist for each instructor pair since the sum of the length of all sections, excluding the longest, assigned to each pair is less than or equal to its previous value. □

Property 2 The bin overflow problem is NP-Complete in the strong sense.

Property 1 maintains that an optimal solution exists with the longest P sections last. Therefore remove the P longest sections and the resulting problem is a bin packing problem which is known to be NP-Complete in the strong sense (see Garey and Johnson 1979). (*i.e.*, After removing the P longest section, is there a partition of S into disjoint sets S_1, S_2, $\cdots$, S_P such that the sum of the length in each S_p is less-than-or-equal-to $\tau_p - 1$.) □

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